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An Investigation of Harmonic Content in a Remote Mine Site

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Abstract:
In order to limit the amount of harmonic content on an electrical network, information about harmonic levels and their source is required. The aim of this paper is to investigate the correlation between the measured harmonics on the electrical network of an isolated mine site, and the modelled predictions based on equipment information. Measurements were performed by a power quality monitoring equipment, and simulations were performed using a sophisticated power systems design package EDSA. The availability of harmonic filters and other methods for the reduction of harmonics makes the need for accurate harmonic modelling of a network imperative. This paper concludes with the explanations for the major differences between the measured parameters and the modelled predictions.

***Keywords*—Harmonic content, Power quality-measurement and simulation, mining network**

1. Introduction

Power quality is now a more important issue for industry, commerce and the home consumer than it was a few decades ago. Because the number of electrical devices that act as nonlinear loads has increased significantly in the past decades, the injection of harmonic content into the electricity network has increased noticeably. With advances in power electronics, harmonic producing equipment such as inverters, rectifiers, variable speed drives, electronic ballast's, and switch-mode power supplies have become widespread in their use. The effect that harmonics have on electrical equipment, in particular sensitive electronic equipment has only become apparent in the last several years. Capacitor failure, computer malfunction, conductor failure, flickering fluorescent lighting, overheating equipment, and power interference in communications are only some of the undesirable side effects harmonics may cause when present in the electricity network. Therefore there is a need to investigate the amount of harmonic content in electrical systems, and to find solutions to remedy the situation so that adverse effects and added costs are avoided.

With the growing concern about the levels of harmonics present in electrical networks, a number of regional standards have been introduced in countries throughout the world [1]. These standards are imposed on electrical items, electricity customers and electricity utilities. There are many standards available; the most widely recognized being the IEEE STD 519-1992 *"IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"* [2].

Harmonics are a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency [2]. With a power frequency (fundamental frequency) of 50Hz in Australia, the equation representing a harmonic frequency is given by

$$f_h = h \times 50Hz, \tag{1}$$

where h is the harmonic order

In order to determine the relative distortion due to harmonics on a power system, the term Total Harmonic Distortion (THD) has been widely used. Total Harmonic Distortion is a measure of the amount of distortion harmonics cause on the system voltage, expressed as a percentage of the fundamental [2]. Both voltage and current waveform distortion may be represented by THD, with Total Harmonic Voltage Distortion (THVD) and Total Harmonic Current Distortion (THCD) being two common terms used to distinguish between the two.

$$THD = \sqrt{\frac{sum\ of\ squares\ of\ amplitudes\ of\ all\ harmonics}{square\ of\ amplitude\ of\ fundamental}} \times 100\% \tag{2}$$

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\% \tag{3}$$

Where

V_h is the RMS value of the harmonic component h

V_1 is the RMS value of the fundamental component

There are many causes of harmonics in a power system. Harmonics may arise in the generation of power, in the distribution system, or from the loads connected to the network. By far the greatest production of harmonics is via harmonic current generation from customers' non-linear loads.

Variable speed drives are a heavy producer of harmonics, as they utilize both rectifying and inverting circuitry in their operation as seen from Figure 1 [3].

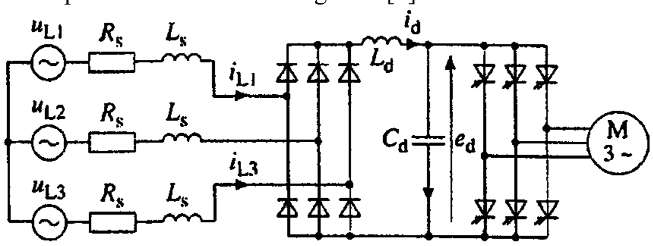

Figure 1. Typical Variable Speed Drive Structure

Variable speed drives may take one of two forms. Voltage source inverter drives use large capacitors to regulate the DC voltage to the inverter [3]. Variable frequency is provided when the inverter chops the DC voltage up into the required waveform. Current source inverters use a similar principle, but use a large inductance instead of a capacitor to regulate the current input to the inverter. The current is then shaped to provide the variable frequency component. Harmonic currents produced by variable speed drives depend heavily on the type of drive, the loading upon the drive, and the characteristics of the system supplying the drive [3].

Cycloconverters are usually used in situations that require high-power and precise control over the speed, allowing low speed operation as well as high speeds. Because the drives to run the motor use thyristors, whilst drawing current pulses the generation of harmonics occur given by (4).

$$f_h = f_1(kq \pm 1) \pm 6nf_O \tag{4}$$

Where

f_h is the harmonic frequency imposed on the ac system

k and n are integers

f_O is the output frequency of the cycloconverter.

The first term, $f_1(kq \pm 1)$ represents the six-pulse converter components and the second term represents sideband characteristic frequencies [2]. Due to the varying amounts of inter-harmonics produced by cycloconverters, it is more difficult to design harmonic filters around these components.

A remote mine site was reported to have some harmonics related problems. A power quality monitor was connected to a number of selected locations on this site. Findings from these measurements will be reported in this paper. The electrical network of this mining site was also analyzed using specialized software. Comparison between the measurement and analytical results will be also discussed in this paper.

2. FIELD MEASUREMENTS

The electrical network of the remote mine site where measurements were undertaken is reasonably large and entirely self-contained. All power for the mine's operation is generated on site with the aid of 22 generator sets. Eighteen of these run on natural gas, with the remaining four generators operating on diesel fuel. All of the generators supply 415V, which is converted to 11kV to supply the main power bus. The majority of loads upon the network are motors drives. Some are ordinary induction motors and synchronous machines, while other loads include variable speed drives and a 1200 kW mine winder cycloconverter. The latter two elements are the major contributors of harmonics in the system, and hence were the primary focus for the measurements undertaken. Figure 2 is a block diagram of the mine electrical network, to give an idea of the location of the various measurements taken.

There are no capacitor banks for power factor improvement on the site, so the main path for harmonic currents to flow is back to the generators through the transmission lines.

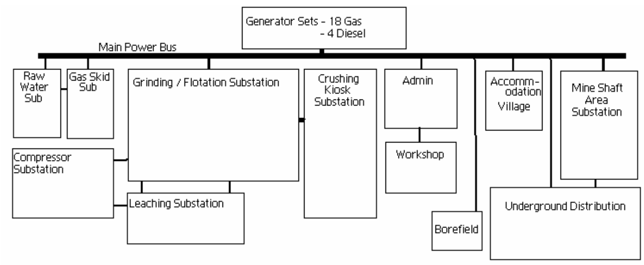

Figure 2 Block diagram of the mine electrical network

2.1 Power Quality Measurement Connections

For all of the measurements taken from the mine site, a power quality measurement device PQNode was used [5]. The device can record wave faults, impulses, harmonics, RMS variations, sags and swells, outages and cold-load pickups. The unit is also capable of continuously monitoring levels of voltage, current, and power factor. The device is capable of measuring and storing the information internally for download into a computer running the associated software (PASS). As the maximum voltage allowable on the inputs is 600V and the maximum current is only 10 Amps, the PQNode device is usually connected through voltage transformers for measuring higher voltages and current transformers for larger currents.

Figure 3 depicts the connection arrangement for the case of an 11kV connection point. In the case of equipment supplied at 415V, voltage connections were made from small circuit breakers associated with the panel instrumentation of the voltage bus enclosures.

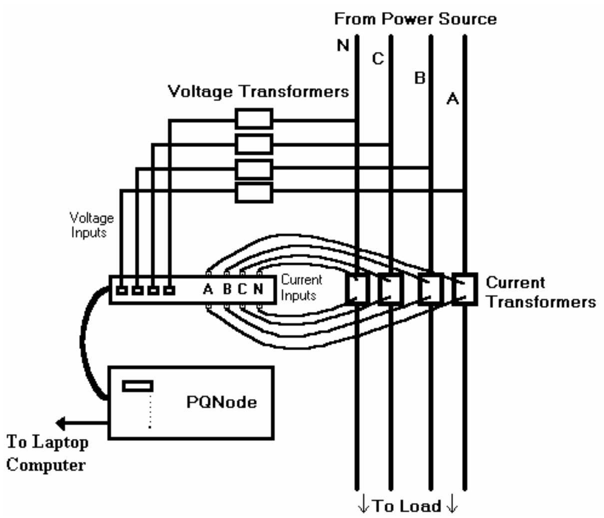

Figure 3 Typical Connection Configuration Used for Measurements

Measurements of voltage and current readings were taken on the mine winder bus, the main power bus, a generator's connection point, and at all buses containing variable speed drive loads. At each point of connection to the system, the measuring device was left to record for the most part every two minutes for a period of 3 hours. Ideally, a longer time period would have been better for the measurements, but time restrictions did not allow this.

Voltage and current readings for the mine winder cycloconverter had to be taken separately due to the distant separation of the control panels required for connections. The mine winder cycloconverter itself consists of two 6-pulse cycloconverters. It is supplied power via 3 three-winding transformers that step down the 11kV to 1000 Volts. The cycloconverter appears like a 12-pulse cycloconverter due to a 30^{o} phase shift between the two 6-pulse cycloconverters. This whole unit then supplies a 12-pole synchronous motor mine winder.

3. RESULTS

3.1 Measured Results

1) Mine Winder Cycloconverter

As the mine winder operates on a cycle (approximately 90 seconds for a full cycle), the measurements obtained for the current measurements contain a significant number of zero readings. These indicate that either the mine winder was not operating at the time the reading was taken, or that it was at the beginning or end of a cycle and therefore at rest. For the non-zero readings obtained, these are spread over the range when the cycloconverter is accelerating, running at full speed and decelerating. For this reason, the results containing zero readings were discarded; the maximum readings obtained were used as a more realistic figure of the worst-case scenario.

Figure 4 displays a break up of the harmonic currents produced by the cycloconverter. As may be seen, the ordinarily fundamental frequency component of 50 Hz is significantly less than the current at 100Hz. Therefore, the fundamental component appears to instead reside at 100Hz. This posed a problem for the software PASS when calculating the Total Harmonic Distortion (THD), resulting in a false value.

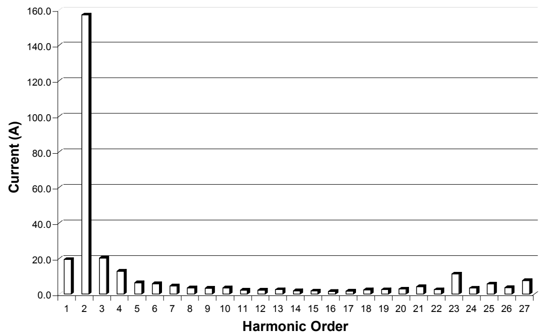

Figure 4 Maximum Harmonic Current Levels on the Mine Winder Cycloconverter

2) *Variable Speed Drives*

On the day that all three measured buses within the flotation substation were taken (Mc49202-Mc49204), the mine winder cycloconverter was not in use. This appears to have had a significant impact on the harmonics results obtained, with both the harmonic currents and voltages remaining consistent during the entire period of measurement. The dominant harmonics are observed at the 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th.

Measurements taken on buses Mc49305 and Mc49306 were recorded on a different day to the other three previous examples, and as a result experienced the effects of the mine winder in operation. Figure 5 shows the average harmonic currents recorded at Mc49306. Interestingly, the second and third harmonics appear to be larger in magnitude than one would expect from the operation of a number variable speed drives. It is also noted that the second and third harmonic currents produced by the mine winder are considerable, and may account for these higher figures. The magnitudes of the harmonics in between the harmonic orders expected from variable speed drive contribution are significantly larger in Figure 5. These appear to support the conclusion that the mine winder is the source of the unusual odd and even harmonics that are not expected from VSD's.

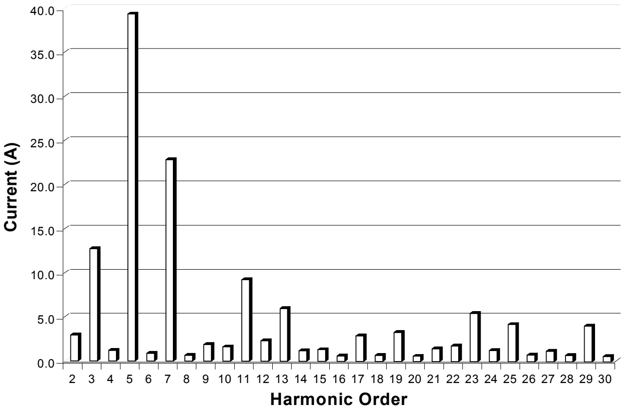

Figure 5 Average Harmonic Currents at Mc49306

i. Generator

As may be seen from Figure 6, there is a significant amount of harmonic current content fed back into the generation plant. This is expected, as the generators are a point of low resistance for the harmonic currents flowing from the variable speed drive loads. The 5th and 7th harmonics present are the most dominant of the harmonic currents, entirely expected from the operation of variable speed drives. However, the even harmonics present in the bunching around the 10th, 11th, 12th and 13th and their magnitude, may only be explained by the operation of the cycloconverter.

ii. Main Power Bus

As this bus connects all of the generating power to buses supplying the loads, harmonic current content will pass through this bus and produce harmonic voltages. The results obtained on the power bus were very intermittent, with certain harmonics present at one reading and entirely absent the next. Therefore to gauge the extent of harmonic voltage levels on the power bus, the maximum harmonic voltages are plotted in Figure 7. The major harmonics associated with variable speed drives are almost the only significant harmonic voltages observed on the power bus.

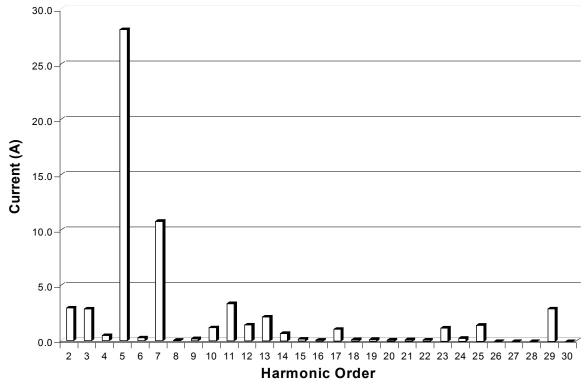

Figure 6 Harmonic Currents Flowing Into Generator No. 9.

Figure 7 Maximum Harmonic Voltages as Percentage of Fundamental: Main Power Bus

3.2 Simulated Results

A model of the complete electrical network of the minesite was created using the software EDSA [6][7], a powerful electrical design program encompassing a multitude of analysis tools. Data from every component of the mine network was taken and input into the model, with load flow analysis and short circuit tests helping to determine the accuracy of the model, with respect to the original mine design.

The manufacturer's data for the variable speed drives and the cycloconverter was used to create harmonic profiles for these devices. There are six main buses on the network those provide power to large harmonic producing loads, and each contains a number of variable speed drive units. For simulation purposes therefore, if there was a

significantly large (kW rating) drive when compared to the rest of the drives on the bus, the harmonic contributions of this drive were assumed to outweigh or overshadow the contributions of the smaller drives. Therefore the harmonic profile of the larger drive was taken when creating the harmonic source for the bus in EDSA.
This should introduce little error as all size variable speed drives display similar harmonic profiles according to information from the manufacturer, with the exception of the very small drives of size less than 46kW. For all of the sources, a power factor of 80% is assumed, as this is close to the actual measured power factor of the mine site.

A diversity factor was also applied to all of the harmonic sources. This takes into account the fact that the loads are not going to act as constant harmonic sources all the time, and will vary with load switching and periods of inactivity. On some of the load buses, there are a number of primary and secondary motor drives, usually of similar power consumption. For the simulation, only one of the drives was assumed to be operating at any point in time, the other used as a backup.

For the harmonic profile of the mine winder, it was assumed to be operating in the accelerating region of its operational cycle. Therefore the harmonic contributions were limited to the 11^{th}, 13^{th}, 23^{rd}, 25^{th}, 35^{th} and 37^{th} harmonics. These values were entered into a generic 6-pulse converter model from EDSA, which supplied information such as angular contributions for modelling the cycloconverter.

Figure 8 shows the simulated results for the harmonic spectrum of the main power bus. It displays similar spectrum components to the actual measured data.

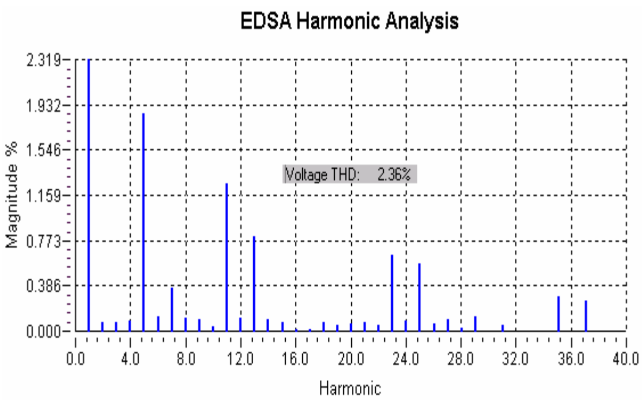

Figure 8 Harmonic Spectrum of Voltage on the Main Power Bus

A feature of the EDSA software is the ability to perform an IEEE 519 Standard harmonic analysis. This checks for violations of the IEEE 519 standard for individual current and voltage harmonics as well as THD for both current and voltage. This was completed on every bus in the network, and the simulation found no violations of the IEEE-519 standard.

4. COMPARISON OF MEASURED AND SIMULATED DATA

One of the major drawbacks to the method in which the experimental measurement was conducted presented itself after the modelling was complete. As there was only access to one power-monitoring device, the measurements taken at the mine were over a period of four days. In this time the plant load changed continuously.

TABLE 1
SIMULATED AND MEASURED TOTAL HARMONIC VOLTAGE DISTORTION LEVELS FOR SELECTED BUSES

Bus	Simulated THVD (%)	Average Measured THVD (%)	Max. Measured THVD (%)
Mc49202	3.15	1.93	2.11
Mc49203	3.40	2.21	2.30
Mc49204	3.04	2.08	2.23
Mc49306	3.13	1.72	2.3
Mc49305	2.83	1.38	2.35
Generator No. 9	1.91	1.74	2.51
Main Power Bus	2.36	1.11	2.74
Mc49901	2.37	1.49	2.63
Mine Winder	2.57	1.60	3.07

However, when modeling the mine site in EDSA, the Total Harmonic Distortion is calculated instantaneously for all of the buses on the network. When doing so, full load conditions are assumed in the software. The only way to avoid this situation would be to have numerous power quality measuring devices all recording at once, and to model the plant conditions exactly as they were at that point in time.

The measured harmonic currents produced by the cycloconverter vary greatly from the harmonic profile used for the simulation. This is due to the nature of operation of the mine winder, with continuously changing operating speeds and loads. Again it is very hard to determine from the measured data and analyzing a reading when the mine winder is operating in the accelerating region. Therefore an accurate comparison to the manufacturer's data is virtually impossible.

Total Harmonic Distortion levels for the three buses mc49202-04 are consistently different between the measured and modelled data. Of course the mine winder cycloconverter was not operating on the day these measurements were taken, which may explain the lower total harmonic distortion levels present. One other explanation, when also considering the differences in the Mc49305 and Mc49306 data, is that the number of drives operating on these buses at the time of measurement is unknown, and may differ to the simulations full load assumption, even with diversity factor taken into account. One other possibility is that the frequent practice of over-sizing plant equipment means that the variable speed drives would never be operating at full load.

The Total Harmonic Distortion measurements for the voltage on the main power bus are in relative agreement with the simulation values if one considers the maximum THD reading obtained from the measured data. Of course to obtain such a maximum value in the measured data, many of the harmonics producing loads must have been operating. This may therefore more accurately match the conditions of the simulation in which all primary loads were considered to be operational.

The generators at the mine site are usually run at reduced load with more generators on line than is required, primarily to account for any unexpected load increases as this situation occasionally arises. In the simulation, 20 of the available 22 generators were required in the simulation to operate at full load to supply the loads. When the actual measurements were taken, only 19 of the generators were running, all at reduced load. Regardless of these differences in operating conditions, the voltage THD values obtained are in close agreement for the simulation and raw measured data.

5. Conclusions

In this paper harmonic analysis of an isolated electrical network has been described. Measured data from the field and simulated results from software modelling were compared for similarities. Measurements were taken by connecting a power quality monitoring device to various points on the electrical network of a mine. Simulations of the electrical networks' harmonic distortion levels were undertaken using EDSA software and electrical data of the equipment on site.

Comparisons were made between:
1. Harmonic currents from variable speed drives and modelled harmonic sources as used in EDSA
2. Harmonic currents from the mine winder cycloconverter and the modelled harmonic source
3. Harmonic voltages on power buses and a generator and the modelled harmonic voltage distortion.

The findings of these comparisons were that:
1. It is difficult to match the exact conditions of the field measurements in the simulation due to the unknown load powers, and the variable nature of a mine or process plant.
2. Modelling of a mine winder cycloconverter is extremely difficult, due to the cyclic nature of the device and the different harmonics injected at different speeds.
3. Overall, the Total Harmonic Voltage Distortion comparisons were reasonably accurate, so for the purposes of checking a network for compliance with IEEE standard 519, the simulation has merit.

6. References

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